The Final Report

Title: Development of a Charged-particle Accumulator Using an RF Confinement Method II

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Contract Number: FA5209-05-P-0280

AOARD Reference Number: AOARD-54047

AOARD Program Manager: William A. Nace, Lt Col, USAF

Period of Performance: 15-Feb-05 – 15-Mar-06

Submission Date: 24 Aug 2006

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **28 AUG 2006**	2. REPORT TYPE **Final Report (Technical)**	3. DATES COVERED **01-02-2005 to 01-03-2006**

4. TITLE AND SUBTITLE **Development of a Charged-particle Accumulator Using an RF Confinement Method II**	5a. CONTRACT NUMBER **FA520905P0280**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Ryugo Hayano**	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Tokyo,7-3-1 Hongo, Bunkyo-ku,Tokyo 113-0033,Japan,JP,113-0033**	8. PERFORMING ORGANIZATION REPORT NUMBER **AOARD-054047**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) **The US Resarch Labolatory, AOARD/AFOSR, Unit 45002, APO, AP, 96337-5002**	10. SPONSOR/MONITOR'S ACRONYM(S) **AOARD/AFOSR**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This report covers research and development of a charged-particle accumulator which ultimately should lead to the entrapment of a large quantity of antiparticles (antiprotons and positrons) and produce a large quantity of antimatter.

15. SUBJECT TERMS
Particle Physics, Positrons

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**11**	

Development of a charged-particle accumulator using an RF confinement method
(FA5209-05-T-0200)

2005 status report

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1 Introduction

The ultimate goal of the development of a superconducting radio-frequency charged-particle accumulator is to trap a large number of antiparticles (antiprotons and positrons), and to produce a large quantity of antimatter.

Antihydrogen atoms have recently been produced using Penning traps with magnetic fields of a few tesla [1, 2]. We here propose a method of producing cold antihydrogen in the 1s ground state by simultaneously confining antiprotons and positrons in a radiofrequency Paul trap [3]. The method has the following advantages enabling high-precision laser and microwave spectroscopy experiments,

1. *point-like antihydrogen source*, radiofrequency fields cause positrons and antiprotons with the lowest energies to fall into a millimeter-sized region at the trap center. This point-like region can be easily irradiated by strongly-focused laser beams, thereby achieving the high photon densities needed to efficiently induce radiative recombination and formation of antihydrogen, and deexcitation to its ground state,
2. *Zero magnetic field*, these antihydrogen atoms are unperturbed by the Zeeman effect as they are produced in a zero magnetic field,
3. *Extraction of antihydrogen*, the antihydrogen are emitted from the trap through numerous openings between its electrodes, and can be used to carry out in-flight antihydrogen experiments,
4. *Selectivity of the 1s state, and antiproton/positron recycling*, only ground-state antihydrogen are emitted, as atoms in the higher-lying states are ionized by the strong RF fields near the edges of the trap; antiprotons and positrons emerging from the ionization are recaptured by the trap, cooled, and recycled to form antihydrogen again,
5. *Compact design*, the trap is relatively small ($\sim$ 20 cm diam) as it requires no superconducting magnet.

2 Linear Paul Trap

2.1 Design

At the end of 2004, after several iterations, the radio-frequency design of the linear paul trap for antiproton trapping/cooling was completed. See Fig. 1. The four rods shown at the bottom are the linear trap electrodes, and the two coils shown in the middle are the inductance coils to achieve the required resonance frequency.

The trap uses $f = 35$MHz to confine antiprotons and resonantly cool at the $f = 10$MHz secular motion frequency to cool the antiprotons in the transverse direction. The estimated cooling time is 1 min. The depth of the trap potential is 1 kV.

The whole structure will be cooled to a superconducting temperature of 1.8 K, otherwise the power requirement (and hence heat dissipation) will be prohibitive.

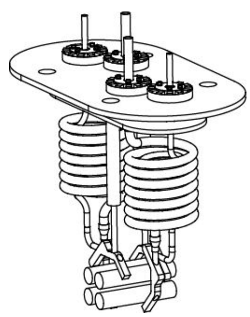

Figure 1 *Linear Paul trap design.*

2.2 Copper model

In 2005, a copper (*i.e., non-superconducting*) model based on the design shown in Fig. 1 was fabricated (see Fig. 2), and its RF resonance behavior was characterized. The test cavity behaved exactly as designed, but we also noted that it is sensitive to external mechanical disturbance (which causes the coils to vibrate, and shift the resonance frequency).

2.3 Test superconducting cavity

High-power superconducting cavities have been developed and used at large accelerators, but they all operate in gigahertz frequencies. To our knowledge, nobody has developed a high-power superconducting cavity working in 10-MHz range.

Before we start the construction of the final trap, we decided to make a test cavity, which is simpler

Figure 2 *Linear Paul copper model. Left: cavity enclosure. Right: bottom view of the model showing the four rods and the resonance coils.*

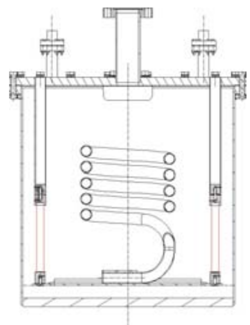

Figure 3 *Linear Paul trap test cavity drawing. The diameter of the cavity is 300 mm. All parts are to be made out of pure niobium, except for the two insulating rods (shown in red), which will be made of sapphire.*

in design, but has all essential features of the final product.

Figure 3 shows the drawing of the test cavity, to be operated at $f = 35$MHz. The diameter of the cavity is 300 mm, and is made of pure niobium (residual-resistivity-ratio RRR=40) with a single coil (instead of two in the final product) and a capacitor (instead of four rods). The design quality factor is $Q > 10^6$. All the niobium parts must be electron-beam welded, and must be surface treated.

With this test cavity, we will study:

1. multipactoring effects caused by the high-voltage RF applied to the cavity,
2. superfluid cooling characteristics,
3. microphonic effects (how the mechanical vibration of the coil affect the resonance frequency)
4. Q factor
5. voltage-standing capability of the sapphire insulating rods (the two red rods shown in Fig. 3.

2.4 Construction of the test superconducting cavity

The fabrication of the test superconducting cavity parts was outsourced to a Japanese company called "Vacuum Products" `http://www.vac-p.co.jp/`, instead of the CERN mechanical workshop, since CERN's workshop was overloaded with the work related to the LHC (Large Hadron Collider) construction. Electron-beam welding of pure niobium is known to be very difficult, and this company, which has supplied many vaccum-related parts to JAERI (Japan Atomic Energy Research Institute) was considered to be one of a few companies which is capable of this difficult task.

Figure 4 *Test cavity parts. Left: outer vacuum chamber, Center: top flange, Right: RF coupler.*

And it turned out to be quite difficult indeed. Especially difficult was the electron-beam welding of the coil, made out of a sheet of niobium. Even a small hole will be fatal, since superfluid helium will "superleak" from any such holes. After 6 months of trial and error, the test cavity is completed (see Fig. 5), ready to be tested in 2006.

Figure 5 *The completed niobium test cavity.*

3 Mechanical and cryogenic design

Our long-range plan made in 2004 showed that we first make the linear Paul trap and a cryostat to cool it down, followed later by the construction of the two-frequency trap. However, mechanical and cryogenic design done in 2005 showed that this approach is impractical, since it is difficult to “extend” the cryostat later to accommodate the two-frequency trap.

We therefore changed our strategy, and have started to design a large cryostat which can cool both the linear and the two-frequency trap.

3.1 Exterior

The “finalized” realistic mechanical design by CERN specialists is shown in Fig.6. This is a 3-dimensional view of the exterior of the cryostat, but the drawing has been done at the parts level, to ensure that this “can be manufactured”. All cryogenic calculations (heat load, helium flow, etc.) has been done.

The outer dimension of the square box at the bottom is about 1m $\times$ 1m $\times$ 1m. There are ports to inject antiprotons and positrons, and ports to extract antihydrogen (see Fig. 7).

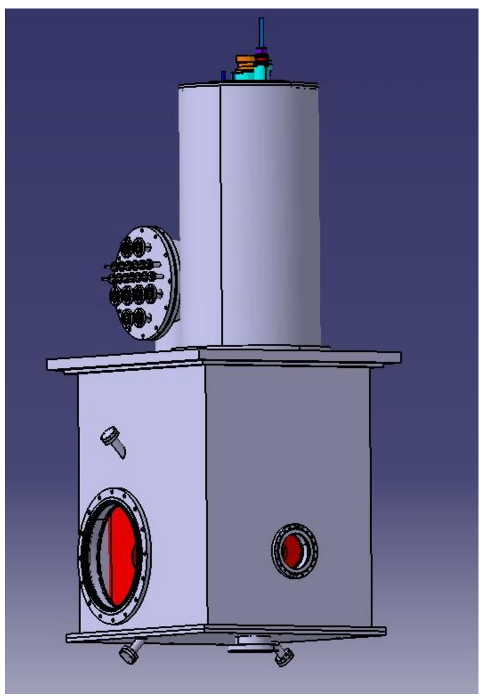

Figure 6 *Exterior of the cryostat.*

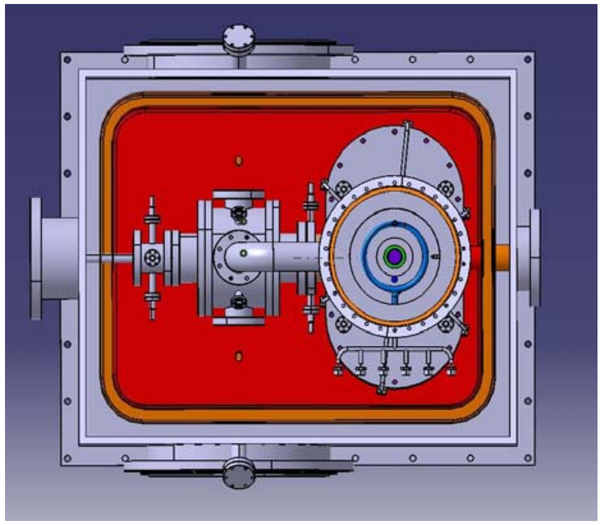

Figure 7 *Cut-away view (seen from top) of the cryostat, showing the two-frequency trap (left) and the resonance coil structure (right). Antiprotons enter the crystat from right, and positrons are loaded from left. Antihydrogen atoms leave the trap from the two side ports.*

3.2 Cooling system

The two superconducting traps will be cooled to a superfluid temperature $T = 1.8$ K, to avoid bubbles and microphonics. A constant-flow cryostat flows liquid helium (300-500 l/day) through the "LHC" heat exchanger (developed for the LHC accelerator cooling at CERN), placed at the center of the cryostat (Fig. 8, blue box at the center). The calculated heat load due to radiofrequency is about 1 W, and there are 6 independent cooling loops to cool the two traps.

The LHC heat exchanger is pumped by a roots pump (pumping speed 2000 m^3/h). There are two radiation screens at 4 K and 20 K, cooled by 4 independent circuits of copper tubes + flow meters at 20 mg/s. No liquid nitrogen is used.

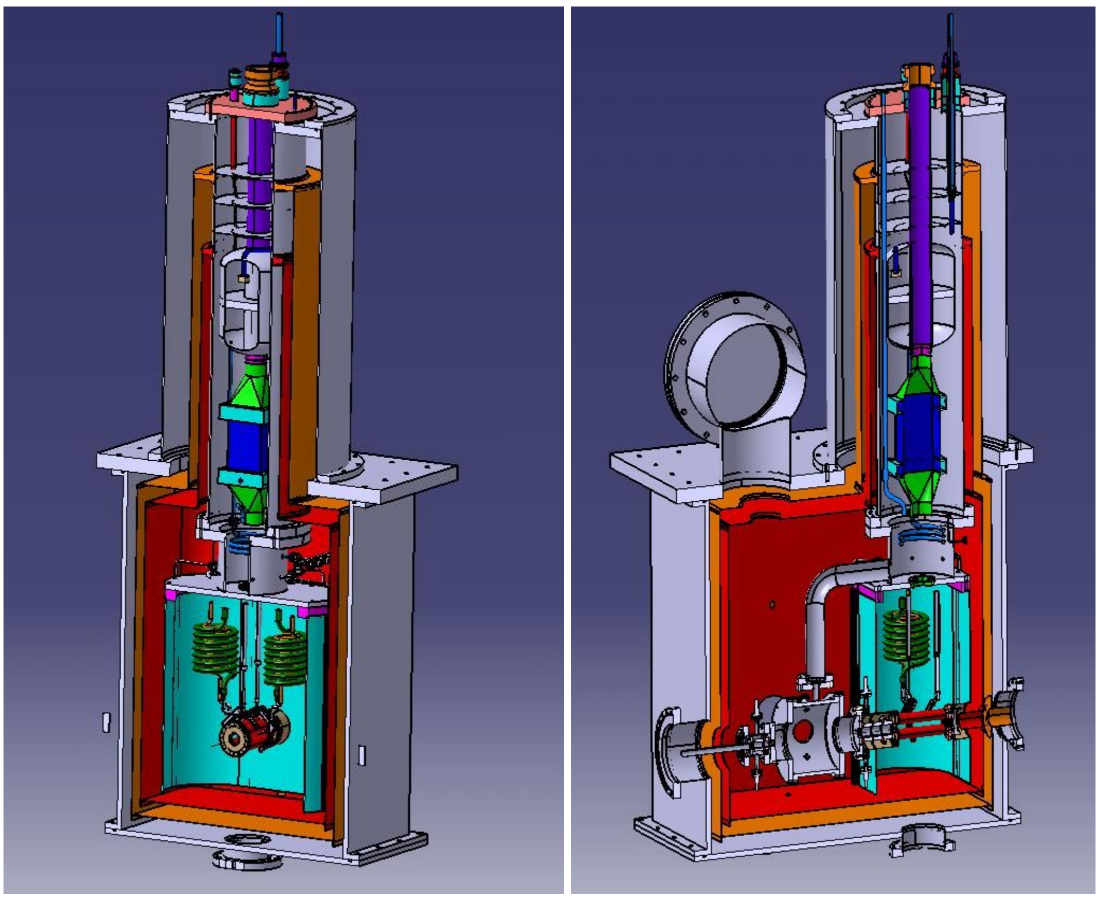

Figure 8 *Cut-away views of the cryostat, showing the heat exchanger (blue square at center), and the Paul traps (bottom).*

4 Two-frequency "recombination" trap

4.1 Status at the end of 2004

The two-frequency trap, designed and prototyped in 2004 (Fig. 9), had the following parameters:

Antiproton confinement	Resonance frequency 2 MHz, RF voltage amplitude 90 V Resistive cooling frequencey 100 kHz
Positron confinement	Resonance frequency 3 GHz, RF voltage amplitude 80 kV Resistive cooling frequency 160 MHz

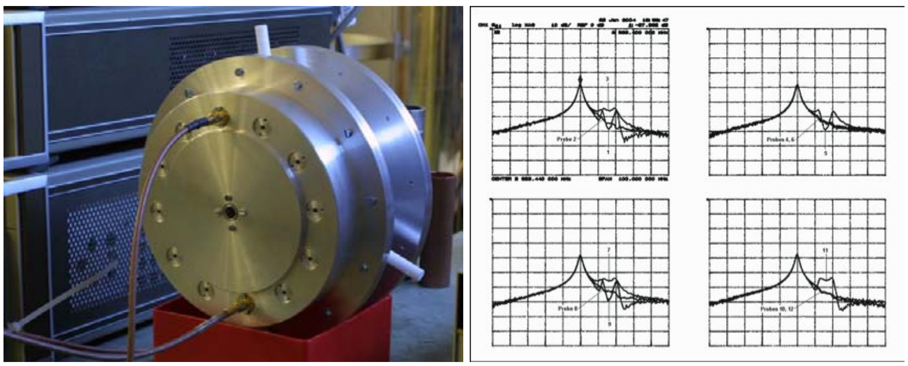

Figure 9 *Two-frequency recombination prototype (left) and its resonance characteristics (right).*

4.2 Problems discovered in 2005

However further studies in 2005 revealed numerous problems with the initial design.

1. Because the 3-GHz RF wavelength is of similar scale with the cavity size, there is an oscillating magnetic field which can disturb the harmonic motion of the particles by 0.1%. (see Fig. 10)

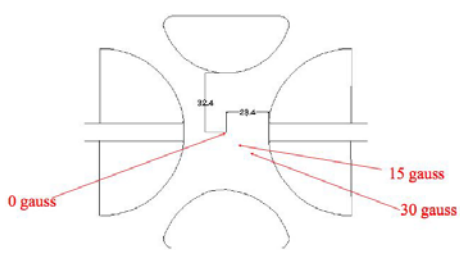

Figure 10 *The oscillating magnetic field amplitudes (induced by the 3 GHz field) at several points in the two-frequency trap.*

2. To capture positrons the 3 GHz RF field in the trap needs to be ramped from zero to 40 kV within 50-100 ns.
   It was expensive and complicated to implement this using high-power GHz klystron amplifiers, and couple the pulsed RF into the cavity.

We decided to use a lower frequency $f = 350$ MHz, wherein solid-state amplifiers could be used - redesign of trap was needed.

The stability condition of Paul traps (voltage scales with the square of the frequency) allows us to work at a much lower voltage(5 kV instead of 80 kV).

4.3 New "realistic" operational frequencies

The new operational frequencies determined based on the 2005 study are as follows:

1. Antiproton injection from the linear trap

Drive frequency	5 MHz
Peak voltage	1 kV (20 kV/m at $z = 1$ cm
Pseudopotential depth	70 V
Axial resistive cooling frequency	650 kHz
Turn-on time	1 μs

2. Antiproton holding
   After antiprotons are captured, they are held in the trap at reduced frequency and voltage:

Drive frequency	1 MHz
Peak voltage	80 V
Axial resistive cooling frequency	260 kHz

3. Positron injection

Drive frequency	350 MHz
Peak voltage	5 kV (corresponds to 95 kV/m at $z = 1$ cm)
Axial resistive cooling frequency	84 MHz
Turn-on time	100 ns (this is not so trivial)

As noted above, the recombination trap must be filled with 1 mJ of RF energy within 100 ns for positron capture.

A P-I-N diode switch successfully transported the 200 MHz RF power from an external storage cavity to the recombination trap within < 100 ns at room temperature, and tests are being carried out at cryogenic temperatures (Fig. 11).

Modifications of the recombination trap design from 3 GHz to 350 MHz based on the above results are now underway.

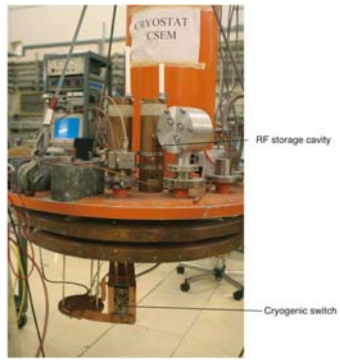

Figure 11 *The recombination trap model cavity and an external storage cavity were used to test the P-I-N diode switch to load the 1 mJ RF energy into the cavity within 100 ns.*

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[2] G. Gabrielse et al., Phys. Rev. Lett. 89 (2002) 213401.
[3] W. Paul, Rev. Mod. Phys. 62 (1990) 531.